

## Technical Note

### Some Effects of Scale on the Shear Strength of Joints

NICK BARTON\*  
 STAVROS BANDIS†

In a recent article, Tse & Cruden [1] pointed out that fairly small errors in estimating the *joint roughness coefficient* (JRC) when visually comparing joint profiles, could result in serious errors in estimating the peak shear strength ( $\tau$ ) from equation (1), (Barton & Choubey [2]), especially if the ratio  $JCS/\sigma_n$  was large.

$$\tau = \sigma_n \tan (\text{JRC} \log_{10} (\text{JCS}/\sigma_n) + \phi_r) \quad (1)$$

where

$\sigma_n$  = effective normal stress  
 JCS = joint wall compression strength  
 $\phi_r$  = residual friction angle

They therefore recommended a numerical check of the value of JRC, based on a detailed profiling and analysis utilizing several of the mathematical techniques for describing surface characteristics used in mechanical engineering, to "avoid the subjectivity of estimates of JRC by comparison with typical profiles."

A key point of Barton & Choubey's recommendations [2] was in fact that *tilt* or *push* tests (shear tests under self-weight induced stresses) were a more reliable method of estimating JRC than comparison with typical profiles. Surprisingly Tse & Cruden [1] did not proceed to the important question of scale effect on shear strength.

#### Scale effect on JRC

In practice it is found that JRC is only a constant for a fixed joint length. Generally, longer profiles (of the same joint) have lower JRC values. Consequently longer samples tend to have lower peak shear strength, as demonstrated conclusively by Pratt *et al.* [3].

Barton & Choubey [2] suggested that the correct size of joint for indexing (shear testing or surface analysis) might as a first approximation be given by the natural block size (specifically the spacing of cross-joints). Rock masses with widely spaced joints have less freedom for block rotation than rock masses with small block sizes. Smaller blocks have greater freedom to follow and 'feel' the smaller scale and steeper asperities of the component joints hence the higher JRC values. This scale effect is illustrated in Fig. 1. (It is appreciated that this freedom for individual rotation may be limited at high stress levels).

In effect the spacing of cross-joints (or block size) is the minimum 'hinge' length in the rock mass, hence its significance as a potential scale effect size limit.

The above scale effect could presumably be simulated by Tse & Cruden's [1] numerical analysis of surface coordinates if larger 'steps' were taken when profiling longer joints. This technique was used by Fecker & Rengers [4] and Barton [5]. In effect, the larger steps jump over the smaller steep asperities, thereby sampling only the longer and more gently inclined asperities which seem to control full scale shear strength, cf. Patton [6]. The shear displacement required to mobilize peak strength seems to be a measure of the distance the

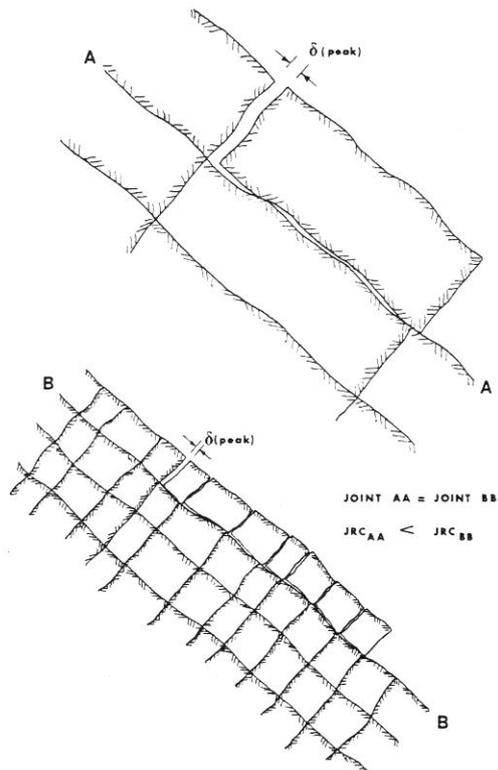


Fig. 1. Scale effect determined by block size, after Barton & Choubey [2].

\* Norwegian Geotechnical Institute, P.O. Box 40, Taasen, Oslo 8, Norway and † Department of Earth Sciences, University of Leeds.

TABLE 1. SIX SETS OF EXAMPLES OF THE SCALE EFFECT ON JRC, BANDIS [7]. COLUMN NO. 1 SHOWS THE RESULTS PRESENTED IN FIG. 2

Joint length Model	Prototype	JRC (cumulative means)					
		1	2	3	4	5	6
60 mm	1.5 m	16.1	16.5	13.9	16.9	11.6	8.7
120 mm	3.0 m	13.8	12.5	12.9	15.7	9.8	7.2
180 mm	4.5 m	10.5	10.5	10.0	12.6	4.8	3.9
360 mm	9.0 m	9.1	6.6	6.1	10.5	5.0	2.3

joint has to displace for contact to be made between those asperities that are effective for that particular joint length. This distance increases with increasing joint length.

A comprehensive series of shear tests by Bandis [7] has clearly demonstrated the scale dependency of JRC. A rubber moulding system was used to take precise impressions of many types of natural joint surfaces in a variety of rocks. A carefully designed model material was used to cast several sets of identical interlocking (jointed) specimens from each pair of moulds. These specimens were shear tested either at full scale (360 mm) or cut into smaller specimens of 180, 120 or 60 mm length. At prototype scale these represented 9, 4.5, 3 or 1.5 m lengths of joint, while the simulated rock had an unconfined compression strength ( $\sigma_c$ ) of 70 MPa. (JCS =  $\sigma_c$  here).

Table 1 shows some typical test results. The probability that JCS also reduces with increasing size [2]

due to the well known scale effect on compression strength probably causes the JRC scale effect to be exaggerated. A constant value of JCS was assumed when back-analysing these tests.

The shape of the shear force—displacement curves also changes significantly with increasing scale. Behaviour changes from 'brittle' to 'plastic', and shear stiffness reduces, as illustrated in Fig. 2. The reason for the changing shape of the curves is that progressive damage occurs to larger and larger asperities as the scale is increased.

#### Influence of block size

Of course a difficulty exists in that the shear box tests are performed on individual jointed blocks. The response of the surrounding rock mass is absent in almost all shear box tests. Although *on an individual basis* small jointed blocks are likely to behave in a more brittle manner than large jointed blocks, *collectively* the much greater number of blocks in a heavily jointed rock mass will tend to cause more 'plastic' behaviour. In addition, it is probable that many heavily jointed rock masses have quite planar joints. This would further emphasise the 'plastic' type of behaviour.

Shear tests on jointed assemblies of rock blocks present serious experimental problems. A simpler approach to the problem can be made via two-dimensional *plane stress* jointed models tested in a biaxial

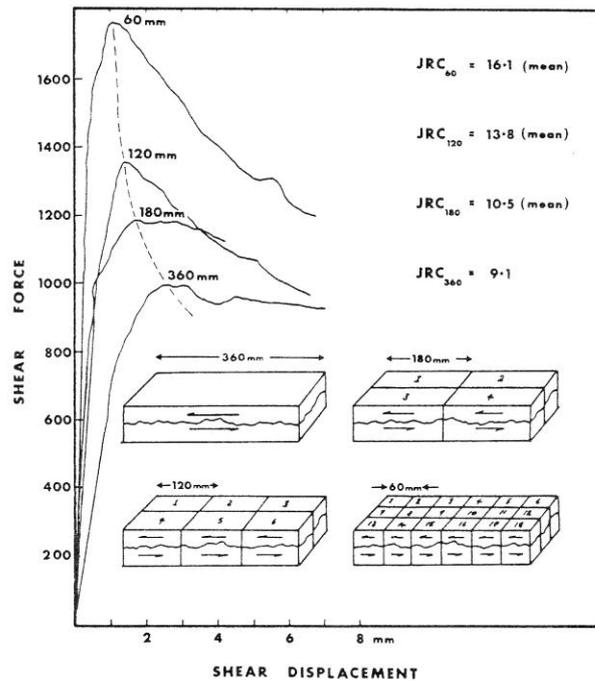


Fig. 2. Behaviour changes from "brittle" to "plastic" with increasing joint sample length. (Cumulative mean curves, Bandis [7]).

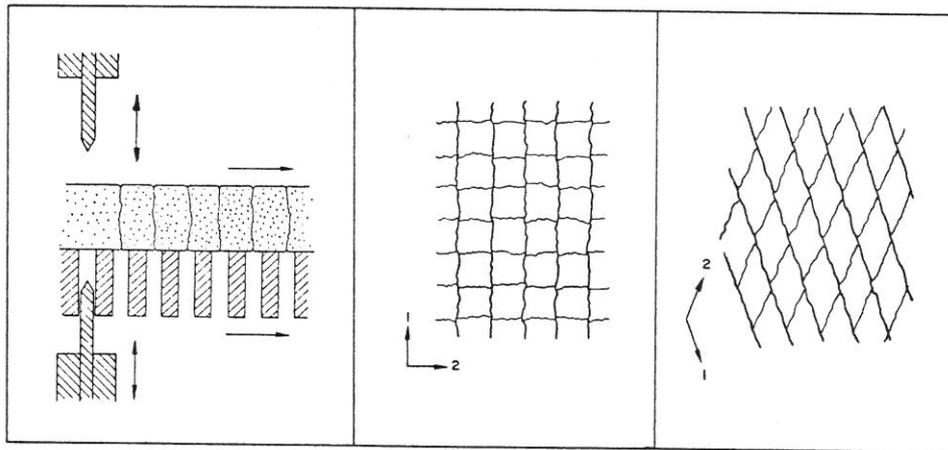


Fig. 3. Method of simulating rough intersecting joints [8].

loading frame. In the tests summarized here three different block sizes were simulated by generating two intersecting sets of tension fractures with spacing 6, 12 or 24 mm. The principle is illustrated in Fig. 3.

Each model consisted of 4000, 1000 or 250 blocks, depending on the joint spacing chosen. The joint orientation ( $2\beta = 36^\circ$ ) and the loading path (constant  $\sigma_2$ , increasing  $\sigma_1$  to failure) were identical in each case. Figure 4 illustrates the principle of the tests.

In *model studies* shear box samples (length  $L_4$ ) are usually larger than  $L_1, L_2$  or  $L_3$  and therefore *underestimate* the shear strength of the jointed mass. In *rock mechanics practice* shear box samples are usually smaller than  $L_1$  and therefore *overestimate* the shear strength of the rock mass.

Table 2 shows the results that were back calculated from the values of  $\sigma_1$  and  $\sigma_2$  required to cause shear failure in the biaxial tests. These results are compared with shear box tests on blocks containing single joints of the same roughness.

The usual problem of insufficient sample size may therefore be reversed in model studies if rough joints are modelled. The 60 and 100 mm long shear box samples of model joints were *too long* to represent the jointed mass, with its much smaller block sizes. Note that this result is the opposite of what is usually observed from smooth block models. The great majority of physical models so far performed in rock mechanics studies have planar joints ( $JRC \approx 0$ ) and lack the important interlocking effect of rough joints.

There may be a tendency amidst the present interest with joint roughness analysis (Tse & Cruden [1], Krahn & Morgenstern [9]) to overlook the fact that the natural block size (or similar) may be the most relevant 'scale-free' size to analyse or test. This is of course considerably larger than the 'laboratory' size specimens usually tested in rock mechanics. The cheapest solution is to conduct *tilt* or *pull* tests on the natural block size of a given rockmass, using gravity alone as the cheap and renewable source of normal stress. The

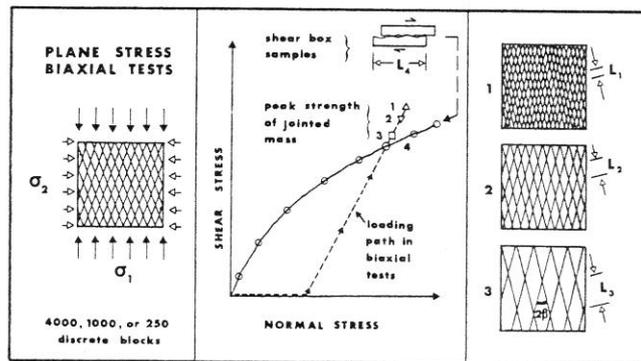


Fig. 4. Shear strength scale effect due to block size.



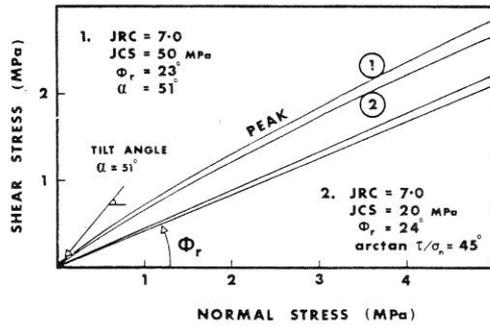


Fig. 6. Peak strength envelopes obtained from results of the hypothetical tilt and pull tests.

**Example 2. Pull test**  
 Assume the following values have been measured and/or estimated:

- N = 2 tons (normal and tangential components of self-weight of upper-block, calculated)
- T<sub>1</sub> = 1 ton
- T<sub>2</sub> = 1 ton (applied by means of hydraulic jack)
- A = 1 m<sup>2</sup> (area of test surface)
- $\phi_r = 24^\circ$  (estimated using Schmidt hammer)
- JCS = 20 MPa (mer, see [2] for details)

$$JRC = \frac{\arctan\left(\frac{1+1}{2}\right) - 24^\circ}{\log_{10}(20/0.02)} = 7.0 \text{ (equation 3).}$$

Once the range of values of JRC have been determined from several such tests, the required peak

shear strength envelopes can be evaluated by substitution in equation (1) over the desired range of normal stress. Figure 6 illustrates the peak shear strength of the above two examples assuming a range of normal stress of 0–5 MPa is of interest.

The advantage of such tests as compared to profile analysis and 'independent' determination of JRC, JCS and  $\phi_r$  is that errors in JCS and  $\phi_r$  are automatically compensated by the physical value of JRC back-calculated.

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